

# Early quark production and approach to chemical equilibrium

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## Motivation:

Quark production determines chemical equilibration time!

### Early-time dynamics:

- Initial conditions provided by effective descriptions, e.g.
- Color Glass Condensate (CGC)**
- Dominated by classical gluon fields
- System evolves towards kinetic and chemical equilibrium

### Previous studies:

- Roles of plasma instabilities and turbulence examined [1]
- Kinetic theory and classical-statistical lattice simulations [2]
- Turbulent attractor at weak gauge couplings found
- Difficult to reach realistic coupling strengths
  - Holography (AdS/CFT)
- Quark production without backreaction [3]

### Our approach:

- Study quark production in 3+1d using **classical-statistical** lattice simulations with  $\text{♂}/\text{♀}$  - fermions and full backreaction
- Determine the impact of different initial conditions
- Increase the number of flavors in order to estimate the effect of **stronger couplings**

## Implementation:

We consider SU(2) gauge theory coupled to  $N_f$  light quarks

$$S_g = \frac{2}{g^2} \sum_x \left( \sum_j \frac{a_s}{a_t} [2 - \text{tr } U_{0j,x}] - \sum_{j < k} \frac{a_t}{a_s} [2 - \text{tr } U_{jk,x}] \right)$$

formulated on a real-time lattice in terms of gauge links

$U_{\mu,n} = e^{ig a_\mu A_{\mu,x}} = e^{ig a_\mu r^a A_{\mu,x}^a}$  and plaquettes:  $U_{\mu\nu,x} = U_{\mu,x} U_{\nu,x+\hat{\mu}} U_{\mu,x+\hat{\nu}}^\dagger U_{\nu,x}^\dagger$

Quark sector consists of the naïve part

$$S_\psi^0 = a_t a_s^3 \sum_{x,\mu} \bar{\psi}_x \left( i \gamma^\mu \frac{U_{\mu,x} \psi_{x+\hat{\mu}} - U_{\mu,x-\hat{\mu}}^\dagger \psi_{x-\hat{\mu}}}{2 a_\mu} - m \psi_x \right)$$

and a spatial pseudoscalar Wilson term:

$$S_\psi^W = a_t a_s^3 \sum_{x,j} \bar{\psi}_x \left( i \gamma_5 \frac{U_{j,x} \psi_{x+\hat{j}} - 2 \psi_x + U_{j,x-\hat{j}}^\dagger \psi_{x-\hat{j}}}{2 a_s} \right)$$

Information about quark production from statistical correlation function:  
 $F_{x,y} = \frac{1}{2} \langle [\psi_x, \bar{\psi}_y] \rangle$

### Methods:

- Quarks integrated out using stochastic  $\text{♂}/\text{♀}$  - approach [4]:  
 $F_{x,y} = F_{x,y}^{\text{sto}} = \langle \psi_x^M \bar{\psi}_y^F \rangle_{\text{sto}} = \langle \psi_x^F \bar{\psi}_y^M \rangle_{\text{sto}}$
- Resulting gluonic action simulated classical-statistically:  
 $\langle O[A] \rangle = \int \mathcal{D}A \int \mathcal{D}A_0 \mathcal{D}E_0 \rho[A_0, E_0] O[A] \delta[D_\mu F^{\mu\nu} - j^\nu]$

### Initial conditions (IC):

- Isotropic fluctuation IC realized by a given gluon distribution:

$$f_g(|\mathbf{p}|, t_0) = \frac{1}{g^2} \Theta(|\mathbf{p}| - Q_s)$$

- Condensate IC with a chromomagnetic field  $\langle B_{i,(t_0,x)}^a \rangle = \delta^{1a} \delta_{i3} B$  leading to Nielsen-Olesen instability

$$\langle A_{1,(t_0,x)}^{q=2} \rangle = \langle A_{2,(t_0,x)}^{q=3} \rangle = \sqrt{\frac{B}{g}}$$

- Condensate IC with an additional chromoelectric field

$$\langle E_{i,(t_0,x)}^a \rangle = \delta^{1a} \delta_{i3} E$$

## References:

- [1] M. C. Abraao York, A. Kurkela, E. Lu and G. D. Moore, Phys. Rev. D 89 (2014) 7, 074036.  
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[4] S. Borsanyi and M. Hindmarsh, Phys. Rev. D 79 (2009) 065010; J. Berges, D. Gelfand and D. Sexty, Phys. Rev. D 89 (2014) 2, 025001.  
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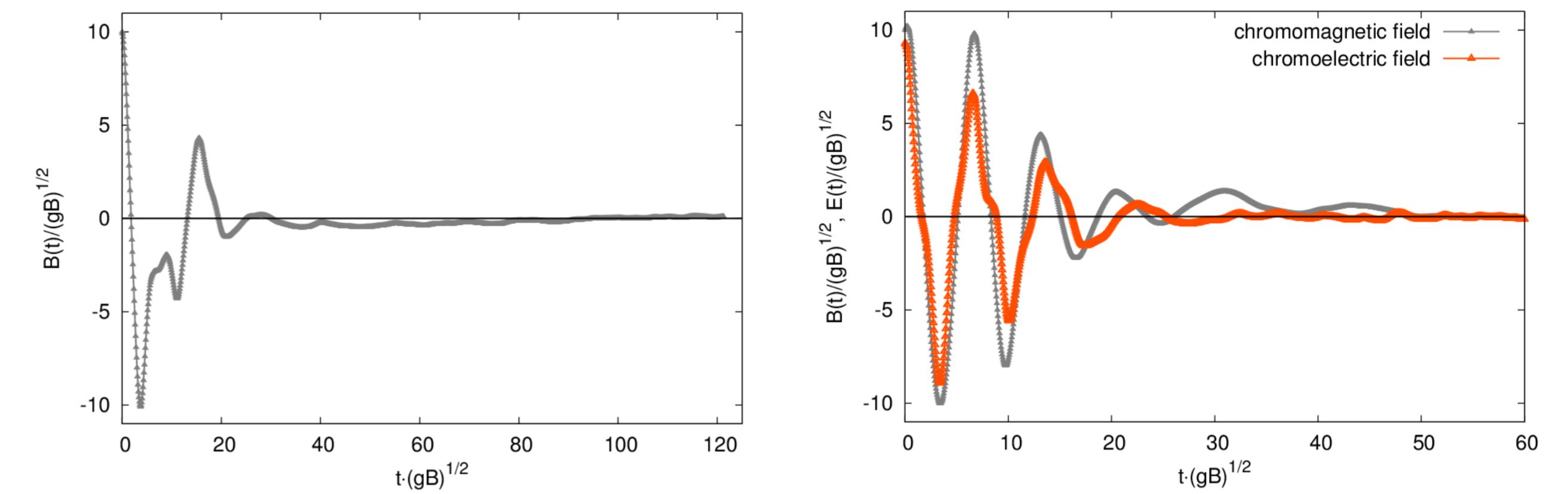


Figure 1: Decay of coherent classical fields

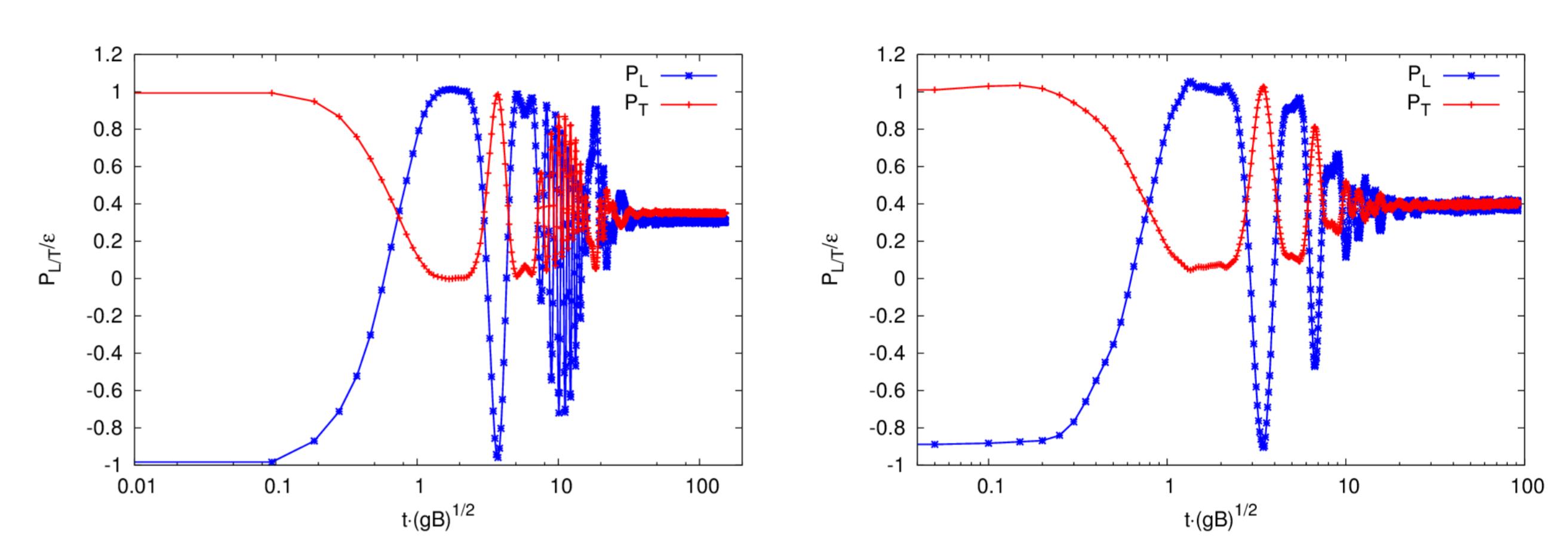


Figure 2: Pressure isotropization

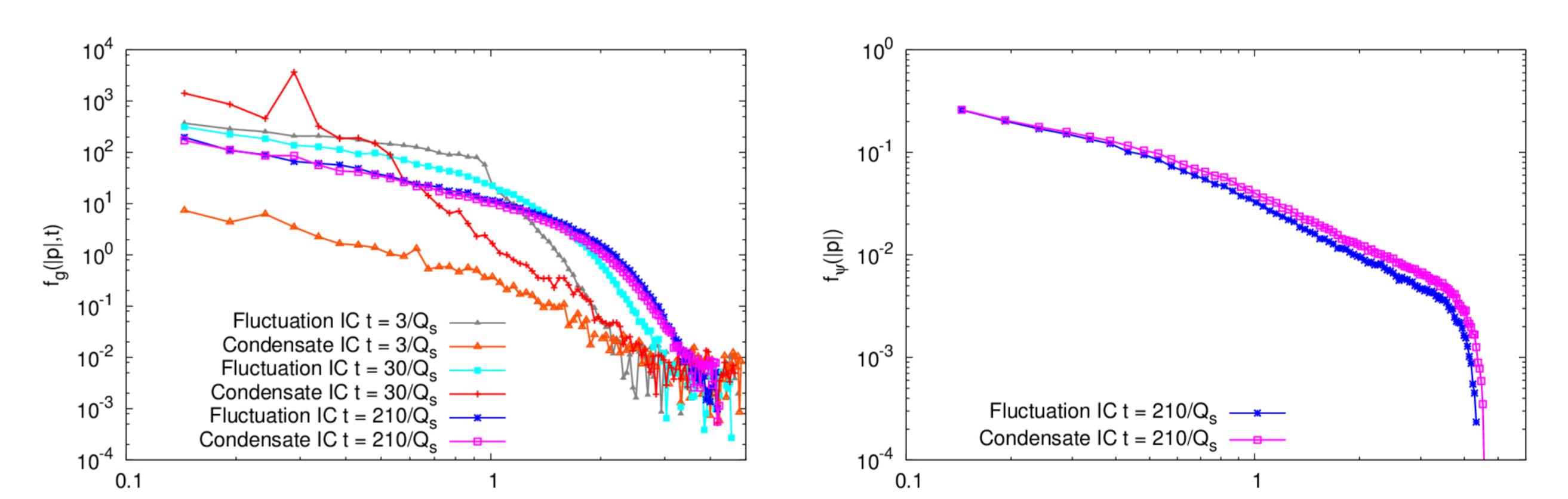


Figure 3: Properties of gluon and quark spectra

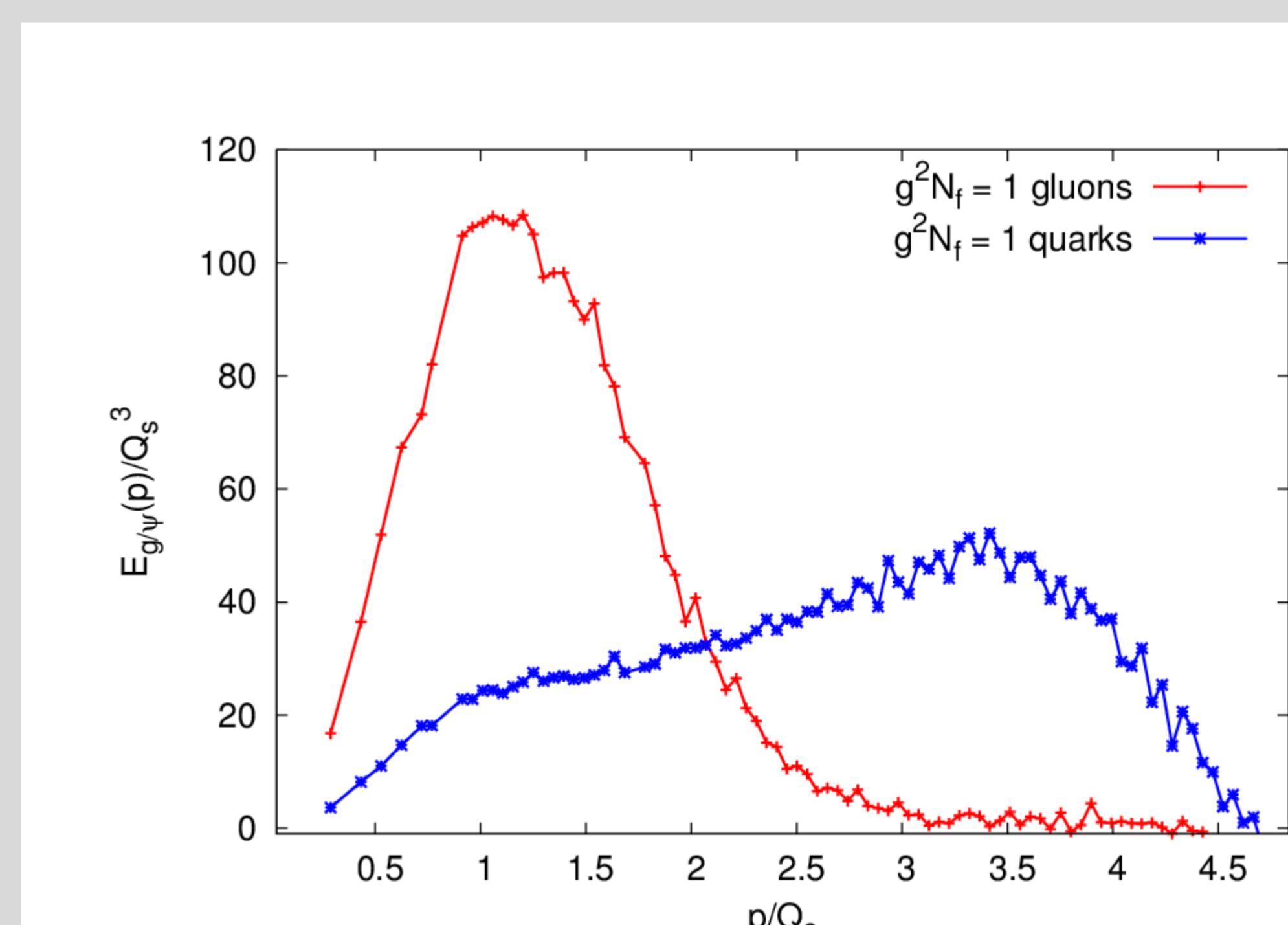


Figure 4: Energy distributions of quarks and gluons in momentum space

## Results:

- Quick isotropization from condensate initial conditions
- Turbulence and universality at weak coupling
- A glance at the strongly coupled regime allows crude extrapolation of the chemical equilibration time:  $t_{ch}^{N_f=1/g^2} \simeq 345/Q_s$  for  $g^2 N_f = 1$

## Colored-Particle-In-Cell (CPIC):

- CPIC simulations offer an alternative approach to early-time dynamics of both quarks and gluons [5]
- Ongoing open-source project: <http://github.com/openpixi>

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